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Simulation study of role of background magnetic field on the magneto-rotational instability in accretion disks

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論 文 内 容 要 旨

The magnetorotational instability (MRI) is thought to be the generation mechanism of turbulence in accretion disks. MRI-induced turbulence leads mass accretion from disks to central objects owing to turbulent viscous effects. Recent simulation studies have also shown that the MRI contributes to various phenomena occurring in accretion disks, such as disk winds (Suzuki and Inutsuka, 2009), mixing of disk gas (Turner and Sano, 2008), and dust sedimentation to the disk midplane (Balsara et al., 2009). Despite the MRI's importance, most recent simulation studies only considered specific configurations of the background magnetic field; i.e., either purely poloidal or azimuthal fields. However, simulation studies of disk formation (e.g., Machida et al., 2000, 2007) suggest that the structure of the magnetic field in accretion disks is complicated. To achieve a thorough understanding of the MRI and the turbulence induced because of it, the effects of the different orientations and intensities of the background field should be clarified.

We investigate the dependence of the saturated state of the MRI in accretion disks on the background magnetic-field properties by performing three-dimensional resistive magnetohydrodynamic (MHD) simulations. We use an original constructed RCIP-CMoCCT scheme with sufficient spatial resolution to adequately solve the fastest-growing MRI mode. We assume an unstratified disk by employing the local shearing-box approximation. Three different uniform-background magnetic-field configurations (net B_z, net B_y, and a net oblique field) are adopted to assess the effects of a wide range of field intensities. These simulations reveal the mechanism controlling the typical time evolution of the MRI's turbulence and suggest that both the intensity and the orientation of the background magnetic field significantly affect the MRI's turbulent motion in accretion disks.

The time evolution of the MRI turbulence varies significantly if the background magnetic field has a finite poloidal component, B_{z0}. We refer to this condition as the nonzero poloidal-flux case; other conditions include

purely azimuthal fields.

In the simulation results assuming nonzero poloidal flux, the evolution of the MRI turbulence is divided into linear and nonlinear growth phases. The MRI's linear growth phase appears during the first three orbits of our simulation runs, when we observe a rapid excitation of the fastest-growing MRI mode, as determined by the dispersion relation. The growth rate of this mode is fixed to three quarters of the rotation frequency, while the mode's wavelength is controlled by B_{z0}. This behavior is similar to that reported in previous simulation studies (e.g., Hawley et al., 1995; Sano and Stone, 2002). We have shown that the MRI's linear growth phase is independent of the azimuthal component of the background magnetic field, B_{y0}, which is consistent with the MRI dispersion relation, because it does not include a term related to B_{y0}.

After the first three orbits, the system experiences a nonlinear turbulent phase. In this nonlinear phase, the mode, which is characterized by a wavelength that is equal to the disk thickness, has the maximum wave amplitude in the system and shows repeated sequences of rapid growth, saturation, and relaxation. A large fraction of the turbulent stress and magnetic energy in the MRI-induced turbulence is dominated by this mode. The mode's characteristic wave pattern satisfies the MRI dispersion relation and is controlled by B_{z0}, while its spatial scale is determined by the disk thickness. In the wave pattern of the largest-amplitude mode, the angle between the velocity and magnetic-field vectors is orthogonal. We show that this wave mode has a large contribution to the turbulent stress and energy enhancements in the nonlinear phase.

The wavelength of the largest-amplitude mode in the nonlinear phase is equal to the disk thickness. We explain this through the magnetic-tension force, which prevents MRI growth, because the longer wavelength leads to a decrease in the magnetic tension. The largest-amplitude mode follows the MRI dispersion relation and, therefore, does not show any B_{y0} dependence. In addition, we show that the growth rate of this mode is consistent with that derived from the MRI dispersion relation; a decrease in B_{z0} results in a small growth rate.

We suggest that the parasitic instability (Goodman and Xu, 1994) plays an important role in saturating the MRI turbulence. According to the dispersion relation, the parasitic instability is expected to have a wave vector that points in the same direction as the velocity vector induced by the largest-amplitude MRI mode. Growth of the parasitic instability leads to disrurb the coupling between the velocity and magnetic-field vectors, and saturates the growth of the largest-amplitude MRI mode. We also clarify the stability condition for MRI turbulence. We suggest that the largest-amplitude mode is suppressed, because the magnetic-tension force becomes larger than the stretching effect from the shear flow. An important contributor to satisfying this condition is related to the amplification of the perturbed component of B_z. Since the parasitic instability causes amplification of B_z, the largest-amplitude mode will be suppressed during the growth of the parasitic instability for the system to satisfy the stability condition.

Since the parasitic instability has characteristics similar to the Kelvin Helmholtz (K-H) instability, we discuss the parasitic instability by analogy to the K-H instability. The growth rate of the K-H instability is reduced by the presence of the magnetic field in the plane of the velocity shear. When B_{y0} has a relatively large intensity and its amplitude is of the same order as that of the largest-amplitude MRI mode, a decrease in the growth rate of the parasitic instability is expected, because B_{y0} has parallel component to the plane of the velocity shear. In addition, the angle of the oscillation plane of the MRI-induced velocity shear (θ_v) is controlled by the B_{z0} intensity. A large B_{z0} value leads to θ_v close to 45° and, consequently, the effect of B_{y0} on the parasitic instability becomes significant. On the other hand, a small B_{z0} value results in θ_v close to 0°, which means that the background field is orthogonal to the velocity-shear plane induced by the largest-amplitude mode, and reduces the effect of B_{y0}. We show that the proposed mechanism is consistent with the results of our simulations.

The saturation amplitudes of the turbulent stress and the magnetic energy are affected by both the poloidal and azimuthal components of the field. In particular, we show that the saturated turbulent stress for $\beta_{y0} \approx 200$ becomes smaller than that for the purely poloidal field when the poloidal component has the same intensity. We show, for the first time, that the background-field dependence of the turbulent stress does not show a simple monotonic trend. We conclude that this dependence is related to the triggering conditions for the growth of the largest-amplitude mode in the nonlinear phase. Investigation of the process triggering the growth of the largest-amplitude mode will be helpful in understanding the behavior of the typical time variation of the MRI in full, as well as the resulting net field dependence of the saturated turbulent stress in accretion disks.

For a purely azimuthal background magnetic field, the time variation is entirely different. In the linear phase of this field configuration, the growth rate increases with increasing background-field intensity, B_{y0}, and the growth time decreases with increasing B_{y0}. The linear phase lasts around three orbits for $\beta_{y0} = 2$, five orbits for $\beta_{y0} = 20$, and ten orbits for $\beta_{y0} = 200$. In the nonlinear state of a purely azimuthal field, our simulation results show a moderate time variation, which is entirely different from that obtained in the nonzero poloidal-flux case. Our simulation results reveal that the saturation amplitude of the turbulent stress is proportional to B_{y0}, while the amplitude is two orders of magnitude smaller than that for a nonzero poloidal field with the same intensity. These results are consistent with previous, unstratified simulation studies (e.g., Hawley et al., 1995).

The anisotropy of the magnetic energy amplified by turbulence is also changed, whether or not the field is purely azimuthal. These results also imply that the time evolution and the properties of the MRI turbulence are altered by the existence of the poloidal component of the background field. For a nonzero poloidal flux, the azimuthal component produces a large fraction of the magnetic energy. This tendency can also be explained by the wave pattern of the largest-amplitude mode.

Despite the fact that the background field affects the MRI turbulence, the correlation between the turbulent stress and the magnetic energy is independent of field topology. Our results indicate that the saturated turbulent stress exhibits a stronger correlation with the power of the perturbed component of the magnetic field than with the power of the total magnetic field.

We also conducted simulations of stratified disks to investigate the applicability of our findings in actual disks. In the region $|z| < 2H$ of a stratified disk with a nonzero poloidal magnetic field, the turbulent stress is consistent with that obtained in unstratified simulations. For $|z| > 2H$, the observed turbulent stress is slightly different from that found in unstratified runs, which is explained by the MRI-induced disk wind. These results indicate that our findings are applicable in the equatorial region of actual disks. On the other hand, in the purely azimuthal field of stratified disks, the saturation amplitude of the turbulent stress is an order of magnitude smaller than that for unstratified disks. We suggest that this difference is caused by the fact that the Parker instability diverts the magnetic flux from the disk plane to outer space and reduces MRI activity.

This study reveals the processes operating in MRI-induced magnetic turbulence from a detailed analysis of the time evolution of the MRI turbulence. These results show that the time variation and the saturation amplitude of the turbulent stress are most significantly affected by the background magnetic field. The variation of the global structure of the disk magnetic field changes both the mass-loading flux from the disk wind and the mass accretion rate caused by the MRI turbulence. We suggest that the time evolution of the global disk structure and the local behavior caused by the MRI mutually interact. Investigation of such interactions is crucial to understanding complicated disk physics, such as planet formation and/or disk evolution.

論文審査の結果の要旨

磁気回転不安定性は、降着円盤における磁気乱流生成機構であり、磁気乱流に伴う角運動量輸送によって中心天体への質量降着を引き起こすと考えられている。しかし、磁気乱流応力の背景磁場配位に対する依存性の系統的な理解は得られておらず、未解決の課題であった。本論文は、降着円盤中の磁気回転不安定性および磁気乱流応力の背景磁場配位に対する依存性を、磁気流体力学の数値シミュレーションを用いて明らかにすることを目的としたものである。本論文では、この目的を達成するために、抵抗性の磁気流体力学シミュレーションコードをRCIP-CMoCCT法に基づいて構築し、降着円盤の局所シアリングボックスモデルを用いて様々な背景磁場配位における磁気回転不安定性の数値実験を実行した。そして、磁気回転不安定性の非線形発展および磁気乱流応力の背景磁場依存性の解明に寄与する以下の先駆的な成果を挙げた。

1. 磁気回転不安定性の非線形段階における磁気乱流応力と磁場・速度・密度変動の空間配位の時間発展を調べ、円盤厚み程度の波長を持つ最大成長モードが、急峻な成長・飽和・緩和を繰り返すことを示した。また、磁場・速度・密度変動の位相関係を解析し、非線形段階における飽和過程には、ケルビン-ヘルムホルツ不安定性型のパラサイト不安定性が本質的な役割を果たすことを明らかにした。さらにケルビン-ヘルムホルツ不安定性との類似から、速度シアーと平行な磁場成分（磁場の方位角成分）が存在するときには、パラサイト不安定性の成長が抑制されることを示唆した。
2. 磁気回転不安定性の非線形段階における磁気乱流応力が、背景磁場の鉛直成分と方位角成分の両者に依存し、単調な依存性を示さないことを明らかにした。特に、磁場の方位角成分で計算したプラズマベータが200となる点において、磁気乱流応力が極小となることを示した。
3. 磁気回転不安定性の非線形段階の緩和過程において、飽和過程でパラサイト不安定性により増幅した磁場の鉛直成分が、磁気エネルギーの急速な減衰を引き起こすことを明らかにした。また、飽和過程における磁気乱流応力は、全磁場強度よりも寧ろ、擾乱磁場強度と高い相関を持つことを明らかにした。
4. 層化型の円盤において数値実験を実行し、背景磁場が鉛直成分を持つ場合は、円盤中央面からスケールハイトの2倍以内の領域においては非層化モデルと同程度の磁気乱流応力が得られ、それより外側では、磁気回転不安定性に駆動された円盤風が生じることを示した。一方で、背景磁場が方位角成分のみを持つ場合は、パーカー不安定性が磁気フラックスを円盤から剥ぎ取り、磁気回転不安定性の活動度を下げることを示した。

本論文は、様々な背景磁場配位における磁気回転不安定性の非線形段階における成長・飽和・緩和過程の詳細を明らかにし、磁気乱流応力の背景磁場配位に対する非単調な依存性を初めて示した先駆性の高いものである。降着円盤では背景磁場は方位角成分を持ち、円盤の時間発展に伴って方位角成分はより支配的となる。背景磁場配位に対する依存性を明らかにした本論文の成果は、円盤の進化に伴う磁気乱流強度の時間発展、延いては中心天体への質量降着、円盤風、円盤ガスの混合、円盤中央面へのダスト沈殿などの時間発展の理解に大きく寄与すると考える。論文およびプレゼンテーションの内容は、背景となる物理の理解、結論および将来展開への提案等、水準に達するもので、著者が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって、齋和人提出の博士論文は、博士（理学）の学位論文として合格と認める。